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Estimation of Soil Erosion and Net Sediment Trapped of Upper-Helmand Catchment in Kajaki Reservoir Using USLE Model and Remote Sensing & GIS Technique

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Abstract**—** *Soil erosion is a serious problem and greatest destroyer to land cover management and resources of the Upper-Helmand river basin catchment. The Upper-Helmand river basin catchment covers an area of 46,793 square kilometers. In the present study, Universal Soil Loss Equation (USLE) model with Remote Sensing and Geographical Information System (GIS) techniques have been used to estimate soil erosion risks and sediment yield at the Upper-Helmand catchment outlet (Kajki reservoir). Potential soil erosion and magnitude are determined in the catchment. Using USLE model, soil erosion map has been prepared and presented, which will be helpful for conservational and management practices to reduce soil erosion and its yield into the reservoir. It is also found that the average soil erosion from the catchment is 6.22ton/ha/year and corresponding sediment yield trapped at the Kajaki reservoir.*

Keywords**—*****Upper-Helmand, Kajaki, USLE, Sediment Yield, Remote Sensing (RS), GIS.***

I. INTRODUCTION

An important item for consideration in the planning and management work of catchment is the soil erosion. It not only reduces the storage capacity of a reservoir but also affects the resources and productivity of catchment. Erosion implicates the process of the detachment, transport and deposition of soil particles and aggregates (Kumar et al., 2015). The total amount of detachment (erosion) of soil and then transportation from its source to downstream control point of the catchment is defined as the sediment yield (Gottschalk, 1964). Therefore, sediment yield rate is the result of soil loss and surface runoff and channel flow. Sediment yield rate basically depends on surface runoff. Therefore, any errors in the prediction of runoff affect the sediment yield. Worldwide, around more than 80% agriculture land and 50% pastureland are suffering from the effect of soil erosion (Pimentel et al. 1995). Dudal (1981) has reported that, globally, fertile land of 60 Mha/year is losing because of soil erosion. Totally degraded land at this rate has been already estimated about 1964.4 Mha of total land (UNEP 1997). Of which, 1903 Mha is degraded due to water, 8.3 Mha is due to wind effect. To predict soil erosion, most of the researchers have faced with problem of use a suitable model for a given watershed (Meijerink and Lieshout 1996). Hence, adaptation of an appropriate model is always a very important decision for the application of critical condition of an area (Chisci and Morgan 1988). Some models have performed well and give good results for a specific area and may not perform well in other areas. Therefore, selection of proper model is very important (Shrestha 2000). Hence, suitable and proper model is the first step for soil erosion modeling.

The original and modified forms of the USLE, is widely used model to assess soil loss from a catchment area (Rao et al, 1994). USLE model has involved number of parameters such as rainfall erosivity factor (R), erodibility factor (K), topographic parameters (LS), vegetative cover (C) and soil conservation practice factor (P). In the present study, Universal Soil Loss Equation (USLE) is being used to assess potential soil erosion from Upper-Helmand catchment and its impact on Kajaki reservoir. Arc-GIS 10.3 software is being used for the generation and development of input digital data for the USLE model to estimate the soil erosion form the catchment and generation of output maps.

II. STUDY AREA

Upper-Helmand catchment is located between longitude 65.092° E to 68.687° E and latitudes 32.254° N to 34.653° N with an area of 46,793 Km2 (Fig. 1). Catchment area is ranging in height between 968 m to 5036 from MSL (Mean Sea Level). The basin area is embodied largely by hills, buried pediments, valleys and

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alluvial plains. The soil textures is silty clay, sandy, loamy and alluvium. The upper-Helmand river basin originated in a westerly extension of the Hindu Kush mountain range near Paghman about 40 kilometers west of Kabul and runs southwesterly for about 590 kilometers to the reservoir of Kajaki Dam. The river water runoff comes mostly from rainfall at the average elevations of the basin in winter and spring season and from snow melting from the glaciers of at the high altitude of mountains which escalate to elevations of 5036m. Range of Annual precipitations varies between 100mm to 670mm and precipitate mostly at higher altitudes during winter and spring season. The Mountains cause many local variations the rainfall erosivity factor (R), soil erodibility factor (K), topographic factor (LS), vegetative cover factor (C) and soil conservation practice factor (P). The upper-Helmand river basin is categorized by a dry continental climate. The temperatures of this region is varying from minus (-) 10 °C in winter to plus (+) 34 °C in summer. The fluctuations in temperature are not uniform in character all over the whole basin.

The catchment is very important in the context of serving inter-sectorial demands including drinking, irrigation and hydropower generation. There is one major reservoir in the drainage basin with gross storage capacity of 1,844 Mm^3 at the existing un-gated spillway crest elevation (Perkins, & Culbertson, 1970).

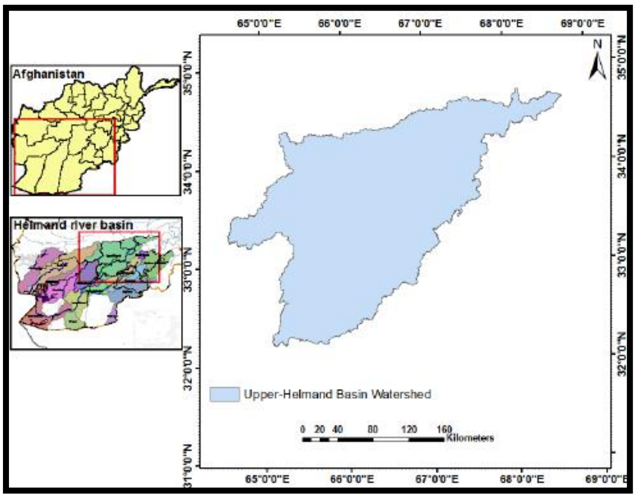

Fig.1 Upper-Helmand Catchment Location Map

III. DATA ACQUISITION

Landsat TM mosaic imagery is downloaded from http://earthexplorer.usgs.gov/. Soil map, soil properties such as soil types, its structure and texture are obtained from the United Nation Food and Agriculture Organization (FAO) soil map. DEM (Digital Elevation model) is derived from ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) and downloaded from http://earthexplorer.usgs.gov/ while 35 years rainfall data is downloaded from global weather.

IV. METHODOLOGY

Several models have been developed for the soil loss erosion over the past 50 years such as, Soil and Water Assessment Tools (SWAT), Universal Soil Loss Equation (USLE), Agricultural Non-Point Source Pollution Model (AGNPS), Water Erosion Prediction Project (WEPP) and Soil Erosion Risk Assessment in Europe (SERAE), etc. Universal Soil Loss Equation (USLE) was developed during 1930 by United State Department of Agriculture (USDA) and widely used for the assessment of soil loss from the catchment in USA. This model predict the average annual soil loss (A), which is the result of five different factors that influence the soil loss and is given below Equation (1) :

$$A = R\,K\,LS\,C\,P \qquad (1)$$

Where A is annual average soil loss (ton/ha/year), R is rainfall erosivity factor (MJ/ha.mm/h), K is soil erodibility factor (MJ mm/ha/ h/ y), L is the slope length factor, S is the slope steepness factor, C is the cover management factor and P is conservation practice factor.

IV.I CALCULATION OF USLE FACTORS

IV.I.I RAINFALL EROSIVITY FACTOR (R)

The rainfall erosivity factor (R) is obtained from the rainfall intensity data. Equation for the erosivity factor from rainfall kinetic energy and rainfall intensity was introduced by Wischmeier & Smith in 1978 and is given by Equation (2):

$$R = k\,Ec\,I30 \qquad (2)$$

Where *Ec* is the kinetic energies, *I30* is the average intensity based on 30 minutes of rain drops of each shower and *k* is a coefficient that depends on the system of units of measurement. In most of the cases the rainfall intensity is not available. Therefore, erosivity factor is determined from the daily rainfall data (Jain et al, 2001). In the Upper-Helmand watershed the rain gauge stations do not have rainfall intensity data. Hence, R is found from mean annual rainfall (P) (Morgan and Davidson, 1991) and is given below by Equation (3):

$$R = 0.5 * P \qquad (3)$$

The annual and monthly precipitation data are downloaded from http://globalweather.tamu.edu/ which covers 42 stations for 35 years. R values are estimated and interpolated over the whole watershed using geostrategic model (Kriging). The R values are varying from 82 to 362 and are shown in Fig.2.

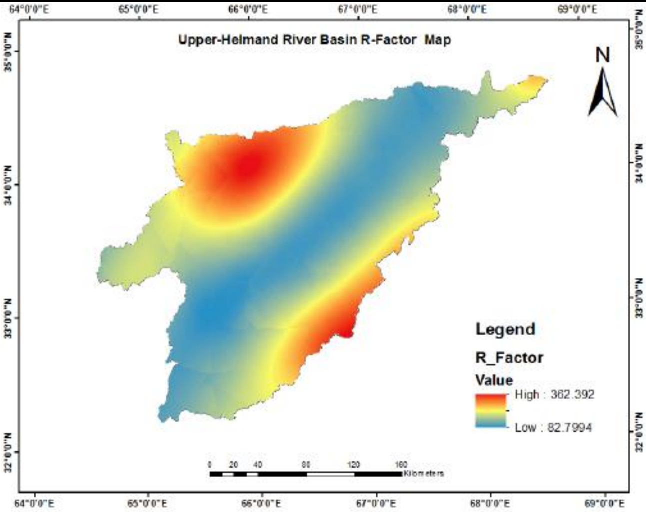

Fig.2: R-Factor Map Upper-Helmand Catchment

IV.I.II SOIL ERODIBILITY FACTOR (K)

The estimation of soil eordibility factor (K) is based on physical properties of soil (texture and organic matter content) (Sharpley & Williams, 1990), and is given in below Equation (4).

$$K = f_{csand} \times f_{cl\text{-}si} \times f_{org} \times f_{hisand} \times 0.1317 \quad (4)$$

Where f_{csand} is a factor of soil which has high coarse sand and gives low soil erodibility through Eq.(5).

$$f_{csand} = \left(0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100}\right)\right]\right) \quad (5)$$

$f_{cl\text{-}si}$ is a factor of soil which has high clay to silt ratio and gives low soil erodibility as obtained from Eq.(6).

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} \quad (6)$$

f_{org} is a factor of soil which has organic carbon content and reduce the erodibility of soil and is given by Eq (7).

$$f_{orgc} = \left(1 - \frac{0.0256 \cdot orgC}{orgC + \exp[3.72 - 2.95 \cdot orgC]}\right) \quad (7)$$

f_{hisand} is a factor of soil which has high content of sand and reduce the erodibility of soil and is given by Eq(8).

$$f_{hisand} = \left(1 - \frac{0.7 \cdot \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9 \cdot \left(1 - \frac{m_s}{100}\right)\right]}\right) \quad (8)$$

In Equation (5) to Equation (8) m_s, m_{silt}, m_c and $orcC$ are the percentage of sand, silt, clay and organic content of top soil respectively. The above factors are calculated in Table.1 from the soil texture of Upper-Helmand catchment based on FAO soil classification. Accordingly, the soil erodibilty factor K is calculated using equation (4) and is given in Table.1 and also shown in Fig.3 for Upper-Helmand river basin.

Table.1: Soil texture of Upper-Helmand catchment bass on FAO Soil Classification.

Soil unit symbol	sand % topsoil	silt % topsoil	clay % topsoil	OC % topsoil	F_{csand}	$F_{cl\text{-}si}$	F_{org}	F_{hisand}	K_{USLE}	K
I	58.9	16.2	24.9	0.97	0.200	0.756	0.925	0.994	0.139	0.0183
JC	39.6	39.9	20.6	0.65	0.201	0.883	0.975	1.000	0.173	0.0227

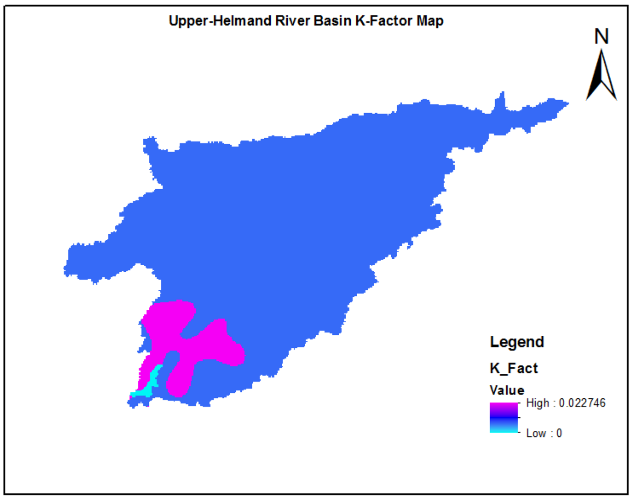

Fig.3 K-Factor Map of Upper-Helmand Watershed

IV.I.III TOPOGRAPHIC FACTOR (LS)

A Digital Elevation Model (DEM) (Fig.4) of 30m resolution images, prepared from Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), and was used to calculate topographic factor (LS). LS is factor combining the product of L and S factors. L factor has computed for each pixel of the gridding Eq.9, (Demet and Govers 1996).

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$$L_{ij-in} = \frac{\left[\left(A_{ij-in}+D^2\right)^{m+1} - \left(A_{ij-in}\right)^{m+1}\right]}{\left(D^{m+2}\right)\times\left(x_{ij}^{\ m}\right)\times(22.13)^m} \tag{9}$$

Where L_{ij-in} is slope length for grid cell (i,j), A_{ij-in} is contributing area at the inlet of the grid cell with coordinates (i,j) (m^2), D is grid cell size in meter, m is length exponent of the USLE L-factor, x_{ij} is equal to (sinαi,j + cosαi,j). The (m) exponent in Eq.9 was used according to the algorithm proposed of McCool et al (1989).

Where, the slope length is function of the erosion ratio of rill to interrill (β).

$$m = \frac{\beta}{\beta+1} \tag{10}$$

Where β varies according to slope gradient (McCool et al.,1989). The β value is obtained by:

$$\beta = \left(\frac{\sin\theta}{0.0896}\right) / \left[3(\sin\theta)^{0.8} + 0.56\right] \tag{11}$$

The slope steepness factor is derived using the following equation (Eq.12a and Eq. 12b) as proposed by (McCool et at., 1987) for slope length >4m.

S = 10.8 sin θ + 0.03 (for slope gradient < 9%) (12a)

S = 16.8 sin θ + 0.5 (for slope gradient ≥ 9%) (12b)

Where S is dimensionless slope steepness factor and θ is slope angle in degree. The variation of LS factor is shown in Fig.5.

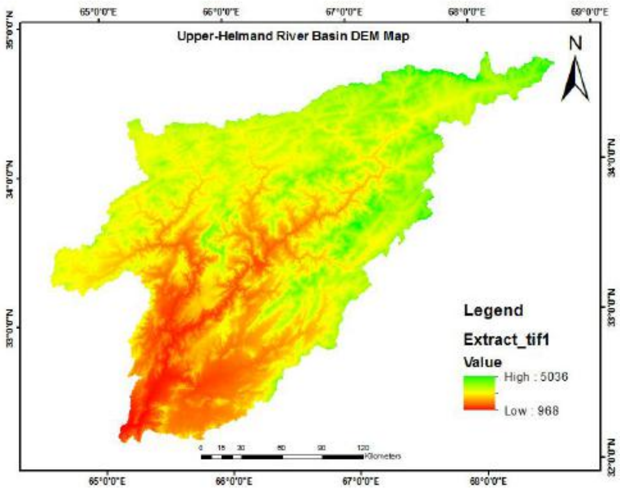

Fig.4 DEM Map of Upper-Helmand Catchment

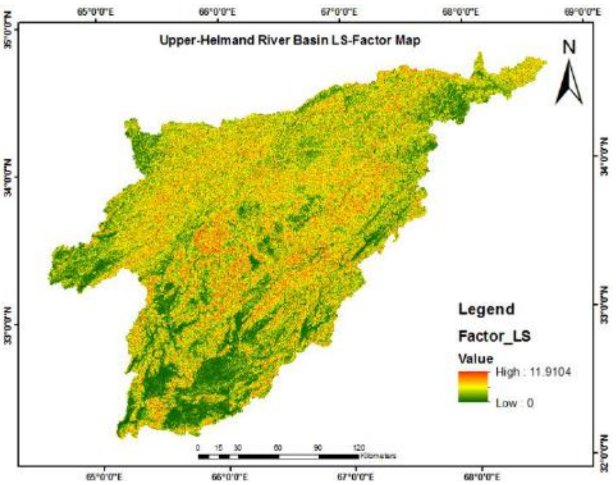

Fig.5 LS-Factor Map of Upper-Helmand Catchment

IV.I.VI COVER MANAGEMENT FACTOR (C_m)

For cover management factor, imagery is extracted from Landsat TM and was used to find out the C_m-factor values bass on LULC and is shown in Fig.6, which clearly shows that the major portions of catchment consist of C_m value equal to 0.4.

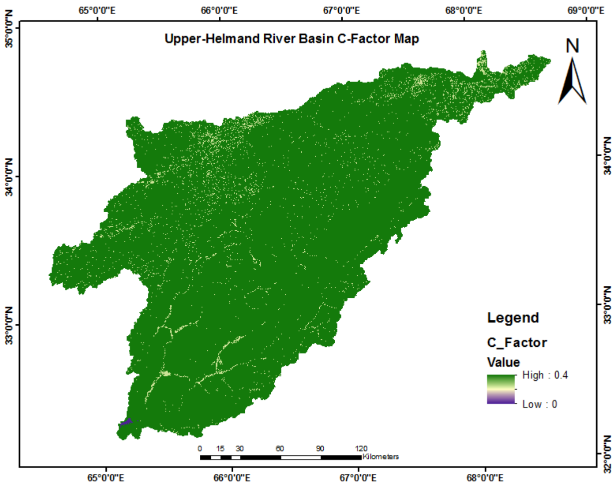

Fig.6 C_m-Factor Map of Upper-Helmand Catchment

IV.I.V CONSERVATION PARCTICE FACTOR

In the catchment there is no erosion control practices, hence the P-factor value is 1 in USLE model.

V. ESTIMATION OF SOIL EROSION USING USLE

The rainfall erosivity, soil erodibility, topographic and crop management factors used in USLE model can be considered as naturally measureable factors determining the sheet and rill erosion processes. Arc-GIS 10.3 has been used to estimate the soil erosion from the Upper-Helmand river basin. Soil erosion from catchment is the results of multiplication of the factors R, K, LS, C, and P. This calculation has been carried out in raster calculation

in Map Algebra of Spatial Analyst Tools, which is a powerful function in Arc-GIS.

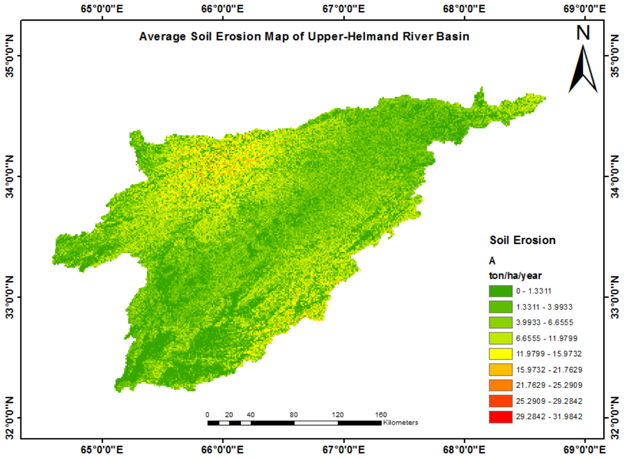

Fig.6 Soil Erosion Map of Upper-Helmand Watershed

Soil erosion value in raster map varies between 0 and 31.98ton/ha/year as shown in Fig.6. Accordingly, soil erosion classification is given in Table.2.

Table.2: Soil Erosion Classification

Erosion Class	Range (tons/ha/ year)	Land Use Class	Area Cover Km^2	Cover Area %
1	0-10	Slight	37865.9	80.92
2	10-20	Moderate	8,229.7	17.59
3	20-31.98	High	697.7	1.49

V.I SEDIMENT YIELD DETERMINATION

The sediment yield equation is expressed as follows:

$$Y = SDR * Ag \qquad (13)$$

Where, Y is sediment yield at catchment outlet, SDR is sediment delivery ratio and Ag is gross soil erosion from the catchment.

Williams and Berndt (1972), related SDR with slope of main channel (SLP) and the corresponding relation is expressed as follow.

$$SDR = 0.627 * SLP^{0.403} \qquad (14)$$

Eq.14 gives reasonable good value for the determination of sediment delivery ratio despite using few parameters of catchment (Williams and Berndt 1972). The estimation of SLP required only two parameters of the catchment the length of channel and elevation of channel.

V.II SEDIMENT TRAP EFFICIENCY

For the determination of sediment trap efficiency, the Brune's Curve (1953) has been used, which is a common and popular method. Brune collected the data from 44 normal pounded reservoirs in USA and developed an envelope curve-ηtrap versus capacity inflow ratio (C/I) Fig.7 and then drawn a median curve, which can be used for the determination of trap efficiency (ηtrap).

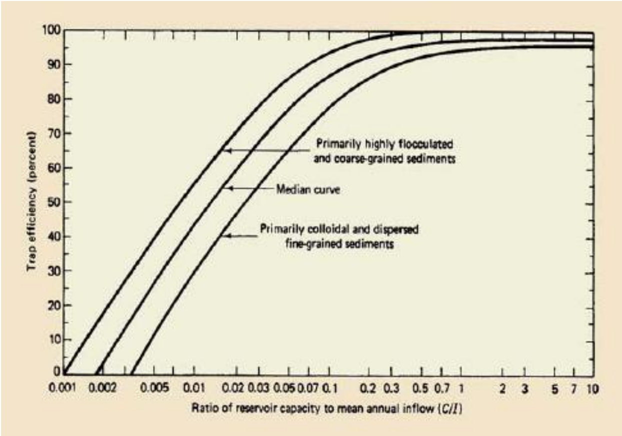

Fig.7 Sediment traps efficiency as per Brune (1953)

VI. RESULTS AND DISCUSSION

The soil erosion rates, as derived from the raster multiplication of the USLE factors are shown in Fig.6, which vary from 0 to 31.98 ton/year. These erosion rates have classified into three classes, slight, moderate and high soil erosion and are given in Table 2. It can be observed that, soil erosion risk is low in 80.92% of the study area with a soil loss of 4.66tons/ha/year, while 17.59% of the area is under moderate erosion with soil loss of 15.31 tons/year. Hardly 1.49% of the area is under high erosion with soil loss of 26.62ton/ha/year. The average quantity of actual soil loss over the whole watershed as estimated by USLE model is 6.22ton/ha/year. Accordingly, the total soil erosion estimated by USLE model was estimated is 29.1 Mton/year over the whole basin. After dividing by the specific gravity of the sediment (1.5tons/m^3) the soil erosion from the Upper-Helmand catchment will be 19.4 Mm^3/year.

VI.I SEDIMENTATION YIELD OF KAJAKI RESERVIOR

The gross erosion from the catchment is estimated, as 19.4 Mm^3/year and the sediment delivery ratio for the watershed is 54%, therefore, the net sediment yields of Kajki reservoir will be 10.47 Mm^3/year. The average trap efficiency of the reservoir is 0.87. This result in the net sediment trapped in the reservoir 8.92 Mm^3/year. The reservoir storage capacity at the crest of spillway was 1,844Mm^3 in 1953 (Perkins, & Culbertson, 1970). At the same spillway elevation 1,033.5m the total storage capacity at present is 1,282 Mm^3. Thus, the total reduction in reservoir during last 63 years will be 562 Mm^3, which results in average reduction in storage capacity as 8.92 Mm^3/year.

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Abbreviation of Table.3:

R = Rainfall Erosivity Factor

K = Soil Erodibility Factor

LS = Topographic Factor

C_mP = Crop Management and Soil Conservation Practice Factor

A = Average Soil Loss

C = Reservoir Capacity

I = Annual Inflows

C/I = Reservoir Capacity Inflow Ratio

Te = Trap Efficiency

SDR = Sediment Delivery Ratio

NS = Net Sediment

Table.3 Soil Erosion and Sediment yield from Upper-Helmand Catchment of 35 years

Year	Rainfall (mm)	R	K	LS	C_mP	A ton/ha/yr	A x 10^6 ton	C 10^6 m^3	I 10^6 m^3	(C/I)	Te	SDR	NS ton x10^6	NS m^3 x10^6
1979	371.14	185.57	0.0205	4.32	0.3872	6.37	29.80	1844	16926.3	0.16	0.87	0.54	14.65	9.33
1980	391.47	195.74	0.0205	4.32	0.3872	6.72	31.44	1844	17757.2	0.15	0.86	0.54	15.28	9.73
1981	326.90	163.45	0.0205	4.32	0.3872	5.61	26.25	1844	14797.1	0.20	0.88	0.54	13.18	8.32
1982	640.02	320.01	0.0205	4.32	0.3872	10.98	51.40	1844	29710.0	0.08	0.80	0.54	23.59	14.80
1983	435.77	217.89	0.0205	4.32	0.3872	7.48	34.99	1844	19071.4	0.14	0.88	0.54	16.63	11.09
1984	388.05	194.02	0.0205	4.32	0.3872	6.66	31.16	1844	17779.6	0.15	0.87	0.54	15.14	9.76
1985	256.67	128.33	0.0205	4.32	0.3872	4.40	20.61	1844	11475.9	0.28	0.90	0.54	10.46	6.68
1986	417.26	208.63	0.0205	4.32	0.3872	7.16	33.51	1844	18651.0	0.14	0.87	0.54	15.74	10.49
1987	313.74	156.87	0.0205	4.32	0.3872	5.38	25.19	1844	14459.5	0.20	0.90	0.54	12.52	8.16
1988	347.23	173.62	0.0205	4.32	0.3872	5.96	27.88	1844	15716.2	0.18	0.87	0.54	13.70	8.73
1989	395.61	197.81	0.0205	4.32	0.3872	6.79	31.77	1844	19016.2	0.14	0.87	0.54	15.10	9.95
1990	426.92	213.46	0.0205	4.32	0.3872	7.33	34.28	1844	19492.5	0.13	0.86	0.54	16.29	10.61
1991	636.68	318.34	0.0205	4.32	0.3872	10.93	51.13	1844	28830.3	0.08	0.80	0.54	23.47	14.72
1992	514.39	257.19	0.0205	4.32	0.3872	8.83	41.31	1844	24018.6	0.10	0.83	0.54	19.41	12.34
1993	310.25	155.13	0.0205	4.32	0.3872	5.32	24.91	1844	14413.4	0.20	0.88	0.54	12.65	7.89
1994	329.71	164.86	0.0205	4.32	0.3872	5.66	26.48	1844	30022.4	0.08	0.80	0.54	12.15	7.63
1995	336.23	168.11	0.0205	4.32	0.3872	5.77	27.00	1844	15354.2	0.19	0.88	0.54	13.27	8.55
1996	314.76	157.38	0.0205	4.32	0.3872	5.40	25.28	1844	13506.8	0.22	0.90	0.54	12.69	8.19
1997	408.75	204.37	0.0205	4.32	0.3872	7.01	32.82	1844	19210.9	0.14	0.86	0.54	15.42	10.16
1998	357.44	178.72	0.0205	4.32	0.3872	6.13	28.70	1844	15845.8	0.18	0.87	0.54	13.95	8.99
1999	201.87	100.94	0.0205	4.32	0.3872	3.46	16.21	1844	8805.6	0.41	0.92	0.54	8.40	5.37
2000	144.10	72.05	0.0205	4.32	0.3872	2.47	11.57	1844	5655.2	0.84	0.95	0.54	6.06	3.96
2001	93.66	46.83	0.0205	4.32	0.3872	1.61	7.52	1844	3640.0	1.88	0.95	0.54	3.98	2.57
2002	217.04	108.52	0.0205	4.32	0.3872	3.72	17.43	1844	9924.8	0.35	0.93	0.54	9.03	5.84
2003	245.03	122.51	0.0205	4.32	0.3872	4.20	19.68	1844	11152.5	0.29	0.91	0.54	9.99	6.45
2004	254.13	127.07	0.0205	4.32	0.3872	4.36	20.41	1844	11063.3	0.29	0.91	0.54	10.36	6.69
2005	371.66	185.83	0.0205	4.32	0.3872	6.38	29.85	1844	15963.7	0.18	0.88	0.54	14.67	9.46
2006	359.78	179.89	0.0205	4.32	0.3872	6.17	28.89	1844	16434.5	0.17	0.88	0.54	14.20	9.15
2007	357.64	178.82	0.0205	4.32	0.3872	6.14	28.72	1844	16516.3	0.17	0.88	0.54	14.11	9.10
2008	291.61	145.81	0.0205	4.32	0.3872	5.00	23.42	1844	12437.4	0.25	0.91	0.54	11.89	7.67
2009	417.32	208.66	0.0205	4.32	0.3872	7.16	33.51	1844	19701.3	0.13	0.84	0.54	15.74	10.13
2010	343.64	171.82	0.0205	4.32	0.3872	5.90	27.60	1844	15394.0	0.18	0.88	0.54	13.56	8.74
2011	435.03	217.52	0.0205	4.32	0.3872	7.47	34.93	1844	18601.0	0.14	0.84	0.54	16.41	10.56
2012	488.98	244.49	0.0205	4.32	0.3872	8.39	39.27	1844	20592.6	0.13	0.50	0.54	18.66	7.07
2013	370.97	185.49	0.0205	4.32	0.3872	6.37	29.79	1844	15719.7	0.18	0.88	0.54	14.64	9.44
2014	532.05	266.02	0.0205	4.32	0.3872	9.13	42.72	1844	20037.2	0.13	0.84	0.54	20.07	12.92

VII. CONCLUSION

In the present study, USLE model and GIS environment has been used to estimate soil erosion. For the generation of various maps under USLE model, the use of GIS platform is a faster and better method for spatial modeling. The USLE model has been accepted broadly all over the world to speculate the soil erosion from a catchment. For generation of USLE factors, remote sensing data was used to generate land use/land cover, soil and topographic data, which are pre-requisite for the model factors. The quantity of average annual soil erosion was estimated by USLE model, as 19.4 Mm^3/year and the sediment trapped in the Kajaki reservoir is as 8.92 Mm^3/year. The validation of USLE model results was carried out with the sedimentation survey (Whitney J W, 2006) which is completed in 2005 for last 53 years from 1952 to 2005. The average annual sedimentation yield in Kajaki reservoir was estimated, as 9.132 Mm^3/year. Therefore, the present study result shows a good and comparable value.

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